EXHUMED PALEOCHANNELS IN CENTRAL UTAH—ANALOGS FOR RAISED CURVILINEAR FEATURES ON MARS

by

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ABSTRACT

Although inversion of relief is a common attribute of landscape evolution, these landforms as a class have been little reported in the terrestrial literature. The Colorado Plateau is a unique geologic setting where multiple exposures of exhumed paleochannels are preserved. Following uplift of the region in middle to late Cenozoic time, erosion by the Colorado River and its tributaries stripped away younger rock strata, revealing Late Jurassic and Early Cretaceous sediments. Fluvial sediments in these paleochannels were indurated by carbonate cements, which made them more resistant to erosion than the surrounding material. As a result of differential erosion, the former valley floors are now preserved as conglomeratic sandstone-capped ridges. The present-day arid climate over the Colorado Plateau has inhibited the development of thick soil horizons and pervasive vegetative cover, both of which would obscure these sedimentary bodies. Exhumed paleochannels expose fluvial sediments and internal sedimentary structures in three dimensions. Multiple examples of individual and superimposed exhumed paleochannel segments are found within the Jurassic Morrison and Cretaceous Cedar Mountain Formations in southeast Emery County of east-central Utah. These sites, located south and west of the town of Green River, Utah, vary in scale and represent a range of depositional environments. This paper illustrates the morphology of these landforms with aerial and ground-based images that highlight the paleochannel form and beautifully exposed sedimentary structures. In addition, we discuss the paleohydrologic conditions and paleoenvironmental factors that influenced channel development, as well as the processes responsible for their ultimate preservation within the geologic record. The morphology of these landforms is similar to comparably sized, raised curvilinear features on Mars. Further study of these terrestrial analogs holds tremendous potential for understanding the time scales and environmental conditions associated with fluvial events in Martian history.

BACKGROUND

Inverted Relief

Inversion of relief can occur wherever materials in valley floors are, or become, more resistant to erosion than the adjacent valley slopes. Multiple processes can lead to the development of relief inversion, including cementation of the valley floor (for example, by ferricrete, silicrete, calcrete, or gypcrete), armoring of the valley floor by coarse grains, and infilling by a more resistant material, commonly a lava flow. Differential erosion removes the less resistant valley slopes and preserves the valley floor as a topographic high (Pain and Ollier, 1995). Various terms have been ascribed to channels preserved in inverted relief including "raised" channel systems (Maizels, 1990), "suspendritic drainage lines" (Miller, 1937), "gravel-capped ridges" (King, 1942), "perched wadis" or "wadi ridges" (Butzer and Hansen, 1968), and "suspenparallel drainage" (Reeves, 1983). In this paper, the term "inverted paleochannel" is used. Inverted paleochannels have been identified in a number of locations around the world, including parts of Arabia and North Africa (Miller, 1937; King, 1942; Holm, 1960; Butzer and Hansen, 1968; and Maizels, 1983, 1987, 1990); New Mexico and west Texas (Reeves, 1983); Wright's Point, Oregon (Niem, 1974; Orr and Orr, 2000); the Ebro Basin of Spain (Friend and others, 1981); and multiple locations in Australia (for example, Mann and Horowitz, 1979; Pain and Ollier, 1995).

Several examples of inverted paleochannels are present within the state of Utah. Many lava-capped channels are located in southwestern Utah, particularly near the cities of St. George, Hurricane, and Virgin where lava flows filled in river valleys 1 to 2 million years ago (Hintze, 1988, 2005; Willis and Biek, 2001; Hamblin, 2004). In fact, the St. George airport is located atop a mesa that is a lava-capped paleochannel. The focus of this paper is inverted paleochannels that were cemented, buried by a thick overburden, and exhumed at several locations in east-central Utah within southeast Emery County (figure 1). These sites, located south and west of the town of Green River, Utah, vary in scale and represent a range of depositional environments.

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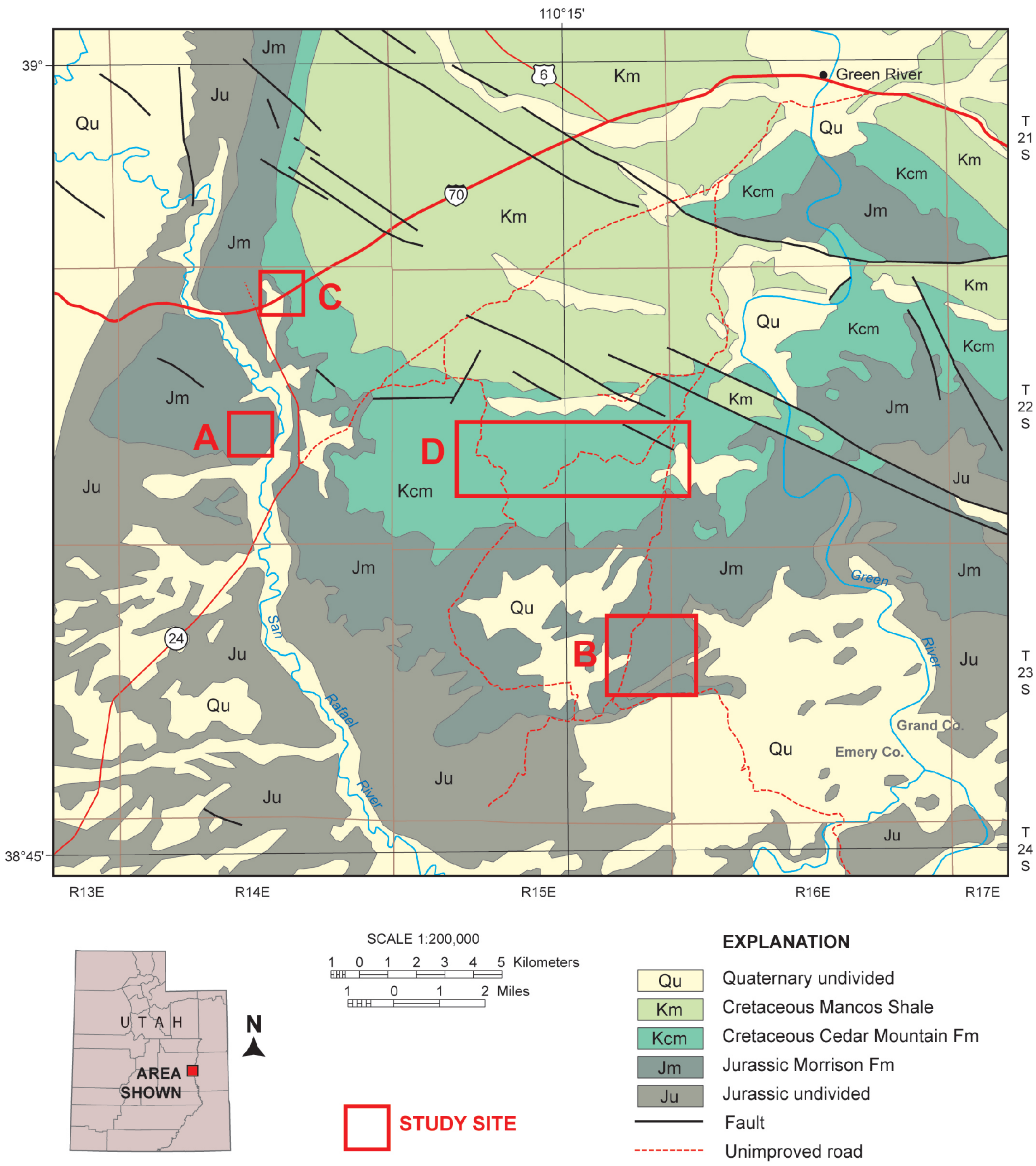


Figure 1. *Inverted paleochannel sites described in text are identified by black rectangles on the geologic map of the study region in east-central Utah (modified from Hintze and others, 2000).*

Geologic Setting

The Colorado Plateau is a physiographic region that extends across western Colorado and New Mexico, and eastern Utah and Arizona. The geologic history of the Colorado Plateau led to the preservation of ancient fluvial systems as inverted paleochannels today. In Late Jurassic time, stream-laid sands and gravels transported from the uplands to the west were deposited on floodplains west of large, shallow lakes that filled and covered the Jurassic Utah-Idaho trough (Peterson, 2001). During this time fluvial channels developed in the Salt Wash and Brushy Basin Members of the Morrison Formation (figure 2). By Early Cretaceous time, the Sevier orogenic belt was emerging in western Utah, while east-central Utah was the site of deposition in alluvial plains, fluvial channels, and floodplains (similar to the depositional environments in the Morrison) with sediments principally derived from a proto-mountain range to the west (Armstrong, 1968; figure 3). Deposition of stream-laid sediments in fluvial environments formed the Ruby Ranch Member (Aptian to middle Albian time) of the Cedar Mountain Formation (figures 2 and 4A; Elder and Kirkland, 1993; Kirkland and others, 1998).

During the Cretaceous, tectonic and climate factors contributed to a rise in global sea level (Prothero and others, 2003, and references therein). High global temperatures, due in part to high atmospheric carbon dioxide levels, melted the polar ice caps and increased the global mass of ocean water. Rapid sea-floor spreading associated with the opening of the Atlantic Ocean began during the middle Mesozoic. This new oceanic basin was shallower than its predecessor, and the net result was a decreased global ocean basin volume. The higher eustatic sea level that existed during the Cretaceous formed a seaway that spread across the interior of North America (figure 4B).

By Late Cretaceous time, approximately 900 m (3000 ft) of marine and marginal marine sediment of the Dakota Sandstone and Mancos Shale had buried the stream-laid deposits of the Morrison and Cedar Mountain Formations in east-central Utah. The basin fill thickened by approximately 1500 m (5000 ft) with deposition of mostly floodplain, fluvial, and lacustrine sediment of the Late Cretaceous Mesaverde Group, the Paleocene-Eocene Wasatch Formation, and the Eocene Green River Formation. The paleochannels remained buried for over 75 million years and were only recently exhumed during regional uplift of the western U.S. in middle and late Cenozoic time.

Rocks now exposed in the Colorado Plateau were below sea level during the Late Cretaceous and are presently at an average elevation of 2.2 km (1.4 mi). There is disagreement over the mechanisms and rate of uplift for the Colorado Plateau during the 80 million year interval since the last marine deposition; however, there appears to be consensus that the uplift rate was rapid over the last several million years (Ruddiman and others, 1989; Sahagian and others, 2002). The major drainage systems of the Colorado Plateau responded to the dramatic base-level change. Drainage patterns that devel-

AGE	STAGE	MAP UNIT		THICKNESS Feet	THICKNESS Meters	Schematic Column
LATE CRETACEOUS	Coniacian-Santonian-Campanian	Mancos Shale		3000	900	
	Turonian		Ferron Ss Mbr	10-30	3-9	
	Cenomanian		Tununk Mbr	350-400	110-120	
		Dakota Ss		0-30	0-9	
EARLY CRETACEOUS	Aptian-Albian	Cedar Mtn Fm	Ruby Ranch Mbr	60-90	20-30	
			Buckhorn Cngl Mbr	20-30	6-9	
LATE JURASSIC	Tithonian	Morrison Fm	Brushy Basin Mbr	240-420	70-130	
	Kimmeridgian		Salt Wash Mbr	160-290	50-90	
	Oxfordian		Tidwell Mbr	20-50	6-15	
MIDDLE JURASSIC	Bathonian-Callovian	Summerville Fm		100-400	30-120	
		Curtis Fm		130-230	40-70	
		Entrada Ss		410-470	125-140	
		Carmel Fm		220-300	65-90	

Figure 2. *Stratigraphic column of lithologic units present within study region in east-central Utah. Shaded units contain exhumed paleochannels.*

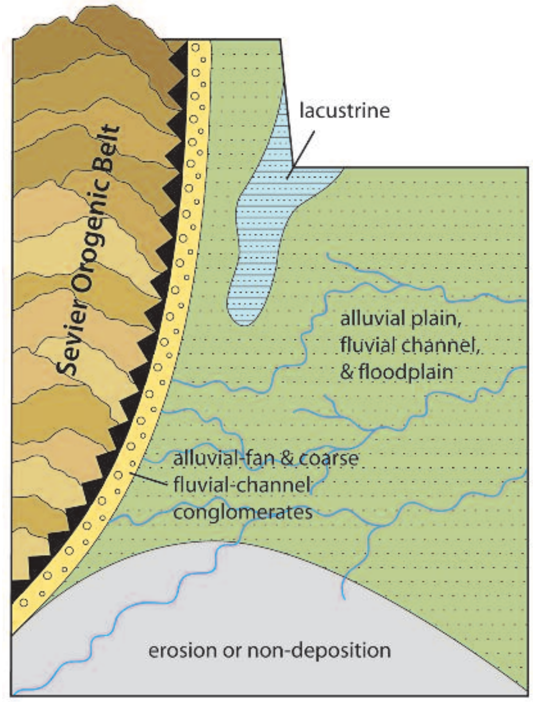


Figure 3. *Paleogeographic map of Utah during Ruby Ranch time (Aptian to middle Albian) with the Sevier orogenic belt in western Utah and various fluvial depositional environments present in east-central Utah (modified from Elder and Kirkland, 1993; Kirkland and others, 1998).*

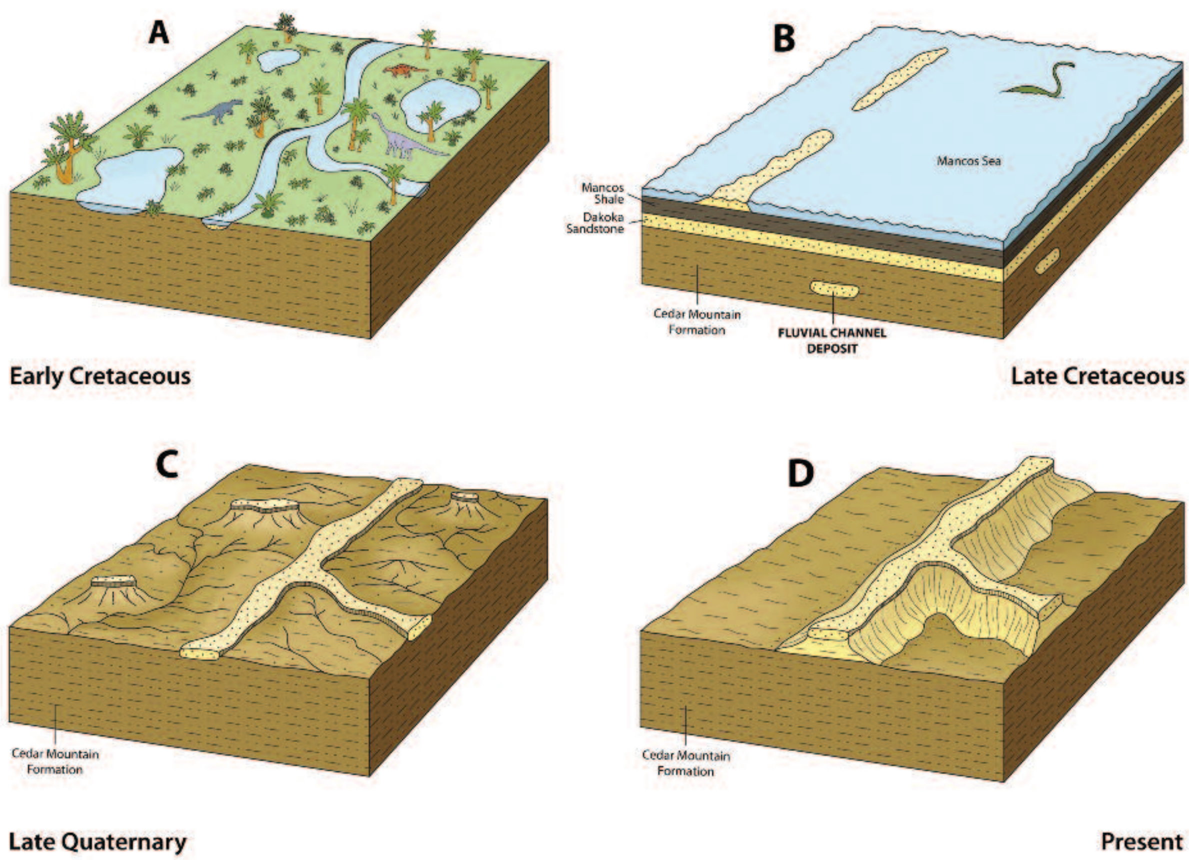


Figure 4. *Block diagrams illustrating the phases of formation in developing an inverted paleochannel for Site D in figure 1. (A) Depositional settings—alluvial-plain, fluvial channel, and floodplain—for the Ruby Ranch Member of the Cedar Mountain Formation in the study region during the Early Cretaceous are illustrated. Schematic includes Aptian to middle Albian-age dinosaurs and plants. (B) In the Late Cretaceous, the study region was beneath a shallow sea. Ultimately, the region was buried by about 2400 m (8000 ft) of sediments and remained buried for over 75 million years. (C) Subsequent uplift and erosion during the middle Tertiary to present stripped away the overburden revealing the paleochannel deposits at the surface today. (D) Present-day expression of inverted paleochannels is preserved as a topographic ridge about 35 m (115 ft) above the surrounding plains.*

oped in east-central Utah during the Oligocene differ from the modern tributary channels to the upper Colorado River, but were apparently the ancestral drainage network that evolved into the modern configuration (Hunt, 1969; see also discussion in Luccitta, 1990). Large volumes of material were transported through these rivers, ultimately resulting in the exhumation of the paleochannel deposits in the Morrison and Cedar Mountain Formations (figure 4C).

Burial history models for the area near Green River, Utah, estimate the removal of 2400 m (8000 ft) of section beginning 37 million years ago (Nuccio and Condon, 1996; Nuccio and Roberts, 2003), equating to a long-term average vertical erosion rate of 0.06 m per thousand years (0.2 ft/kyr). Estimates of incision rates for the Colorado River during the Quaternary provide some evidence to suggest that higher overall erosion rates may have occurred on the Colorado Plateau recently. Estimates of stream incision rates range from 0.18 m per thousand years (0.59 ft/kyr) for the Colorado River over the past one million years (Willis and Biek, 2001; Pederson and others, 2002), to as much as 0.4 to 0.5 m per thousand years (1.3–1.6 ft/kyr) for the Colorado River and some of its major tributaries over the past several hundred thousand years (Davis and others, 2001; Hanks and others, 2001; Marchetti and Cerling, 2001). Increased precipitation associated with the Pleistocene climatic changes in the region would enhance erosion.

The modern climate over the Colorado Plateau has also been critical to the preservation of the paleochannels. Under the current arid climate, the development of thick soil horizons and pervasive vegetative cover has been inhibited. Thus, the inverted paleochannels are readily discernible in the landscape today (figure 4D).

EXAMPLES

Sites in East-Central Utah

Several inverted paleochannels are present within the study region that document a range of paleofluvial environments including point-bar, overbank, and channel (Derr, 1974; Harris, 1980; figure 1). Many of the inverted paleochannel examples are isolated segments. Some of the inverted paleochannels are superimposed upon one another, providing a chronological record of the fluvial environment, as illustrated atop Shadescale Mesa (figure 5, Site A in figure 1). Note in this example the variation in preservation between different channel segments with some inverted paleochannels largely intact and other segments weathered to boulders with sections removed. Large-scale depositional sites are also preserved in inverted relief. For example, a multi-storied distributary-channel fan complex is exposed within the Salt Wash Member of the Morrison Formation (Doelling, 2002; figure 6, Site B in figure 1). Individual inverted paleochannels within this complex are laterally traceable for distances over 4 km (2.5 mi).

Derr (1974) mapped three, isolated, carbonate-cemented paleochannel segments within the Brushy Basin Member of the Morrison Formation west of Green River along Interstate 70 (Site C in figure 1). The oldest inverted paleochannel segment, located south of the interstate, shows no evidence of superposition or other channels. Preserved fluvial sediments in this inverted paleochannel range in size from coarse sand to pebble, and are poorly sorted. The inverted paleochannel was apparently preserved as a result of avulsion, a change in stream course that caused rapid deposition of both bed load and suspended load material (Derr, 1974). Two younger inverted paleochannels are aligned nearly perpendicular to the highway, resulting in beautiful vertical exposures of graded bedding from conglomeratic bases to medium and fine sand at their upper exposed surfaces. Trough cross-beds dominate the surface of the inverted paleochannels and indicate paleocurrent direction was dominantly to the southeast. In contrast to the older channel, these inverted paleochannels are interpreted as part of a meander (point-bar) complex (Derr, 1974). Applying empirical relations from modern streams (Schumm, 1968, 1972) to these inverted paleochannels, Derr (1974) calculated a shallow average paleofluvial gradient of 0.4 m per km (2.0 ft/mi) and average discharge rates ranging from 8 to 120 cubic m per second (300–4200 ft^3/s).

The longest known inverted paleochannel system on the Colorado Plateau consists of four conglomeratic/sandstone-capped ridges, some with bifurcations along route, and numerous shorter ridge segments within the Ruby Ranch Member of the Cedar Mountain Formation (figure 7, Site D in figure 1). The stages of formation for this site in eastern Emery County, Utah, are illustrated in figure 4. Harris (1980) mapped the site and found individual inverted paleochannel segments with lengths that range from 4.5 to 8 km (3–5 mi). The inverted paleochannels stand 30 to 40 m (100–130 ft) above the surrounding plains, with channel sediments evident in the exposed top 5 m (16 ft) of the ridge. Channel form is generally linear, although some sections exhibit low sinuosity with sinuosity ratios between 1.2 and 1.5 (figure 8; Harris, 1980). Multiple stages of paleochannel activity are preserved here and channels were not all formed contemporaneously. In one location, the north-south-trending channel segment overlies a stratigraphically lower channel that extends to the east (figure 9). Channel morphology was used to calculate paleochannel characteristics, again based on empirical equations derived from modern channels by Schumm (1963, 1972). Harris (1980) reported the paleochannels had shallow gradients, 0.23 to 0.38 m per km (1.2–2.0 ft/mi), and annual discharge rates ranging from 20 to 620 cubic m per second (700–22,000 ft^3/s). Paleocurrent direction was determined by analyzing cross-bed orientations (figure 10) and indicates sediment transport direction was to the east-northeast.

Inverted paleochannel surfaces at this site preserve both sand-sized channel-fill deposits and coarser grained

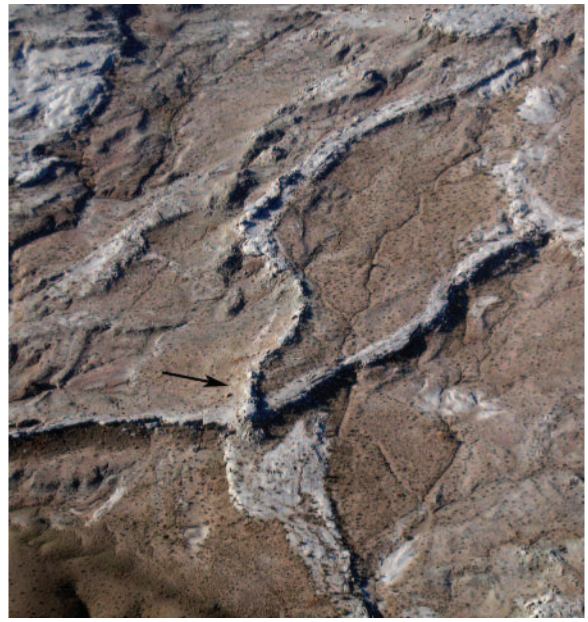


Figure 5. *Oblique aerial photograph of overlapping inverted paleochannels (arrow) in the Salt Wash Member of the Morrison Formation atop Shadescale Mesa (Site A in figure 1). Some of the paleochannel segments exhibit discontinuous preservation and are weathering to boulders. Image width is approximately 360 m (1200 ft) and north is towards bottom of image. Illumination is from left.*

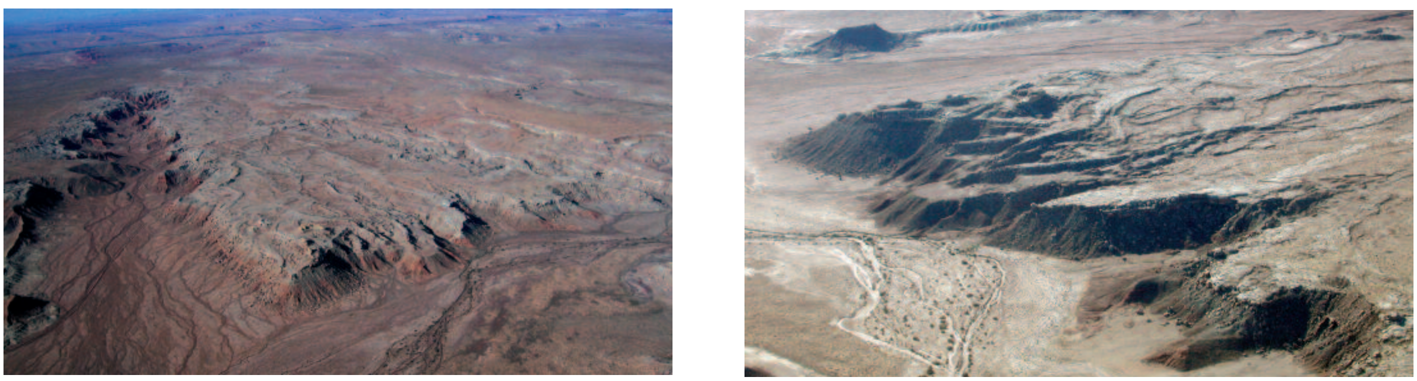


Figure 6. *Left: oblique aerial view to the southwest of distributary fan complex (Site B in figure 1) that is part of the Salt Wash Member of the Morrison Formation. Image width is approximately 1200 m (4000 ft). Illumination is from the left. Right: enlargement of distal margin under different illumination (view to southeast) illustrates the cross-cutting relationships of different paleochannel segments. Total relief from plateau floor is about 65 m (200 ft). Image width is approximately 1200 m (4000 ft). Illumination is from the top.*

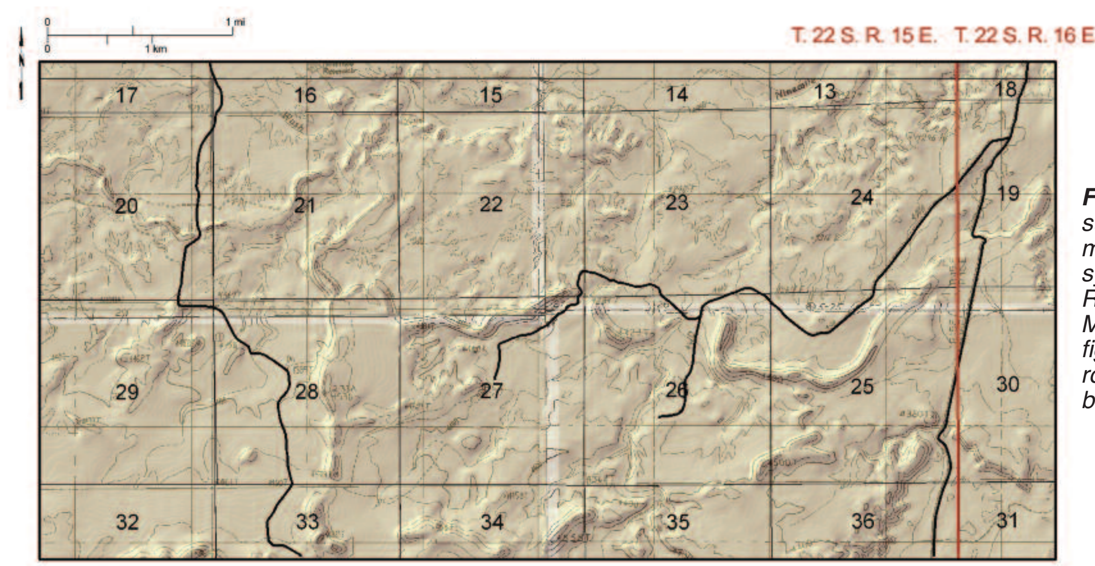


Figure 7. *Aerial photograph superimposed with topographic map of a large paleochannel system that is part of the Ruby Ranch Member of the Cedar Mountain Formation (Site D in figure 1). Black lines are dirt roads. Illumination is from the bottom.*

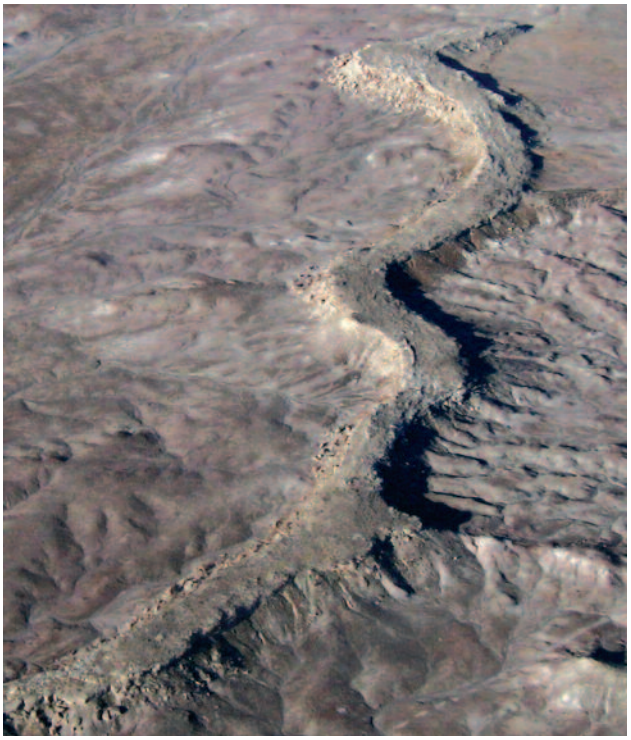


Figure 8. *Oblique aerial photograph of sinuous paleochannel segment with a total length of about 820 m (2700 ft) located at Site D in figure 1. North is to the lower right. Illumination is from the lower left.*

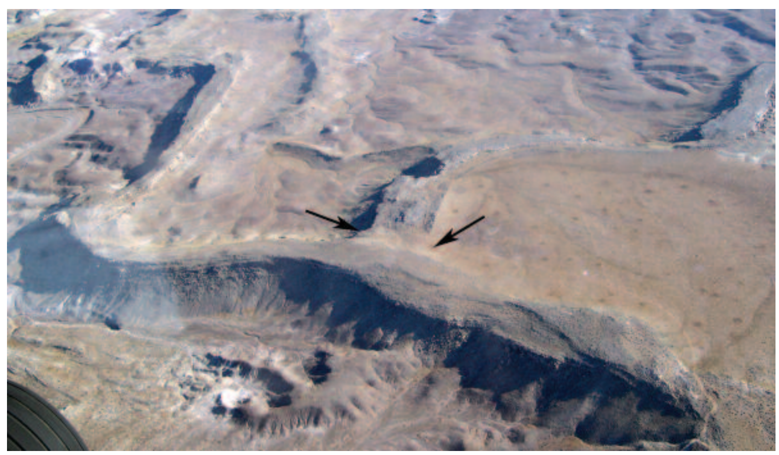


Figure 9. *Oblique aerial photograph of multiple paleochannel segments at Site D in figure 1. Channel segments did not form simultaneously and the apparent bifurcation at center of image (arrows) is two segments at different topographic and stratigraphic levels. The inverted paleochannel segment from lower right to upper left (south to north) in image is stratigraphically higher than the shorter paleochannel segment that extends toward the upper right (east). Image width is approximately 1250 m (4100 ft). North is to upper left. Illumination is from the upper right.*

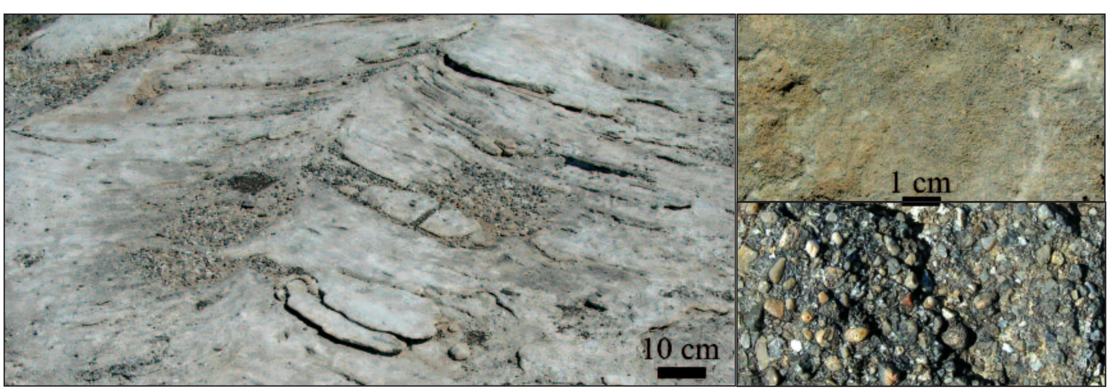


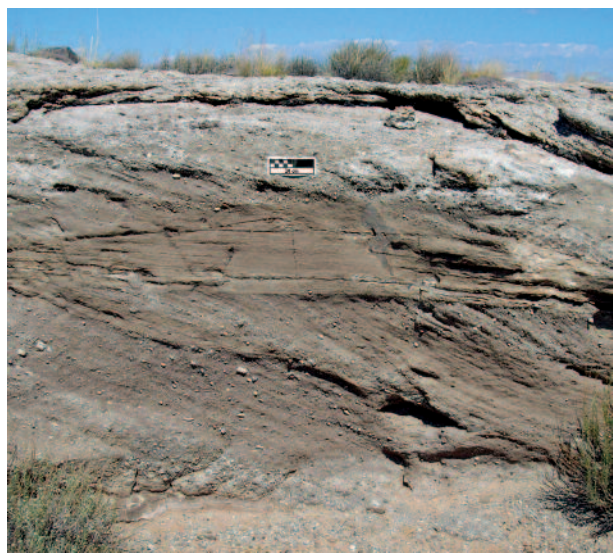
Figure 10. *Inverted paleochannels preserve sedimentary structures and attributes of channel sediments. Photos are from site D in figure 1. Left: trough cross-beds are evident at the channel surface (north-south paleochannel segment in figure 9) and provide a record of paleocurrent direction. View is towards north, in the downstream direction. Top right: quartz sandstone in channel-fill deposit. Bottom right: coarse sediment in point-bar deposit.*

point-bar deposits located on the inside inflections of channel bends (figure 10). Channel fills rise 1.5 to 5 m (5–16 ft) above the point-bar deposits and commonly exhibit scour-and-fill structures throughout their vertical sequence. Channel-fill deposits erode into a relatively smooth surface, vertical cliffs, and variable channel widths, whereas weathering of point-bar deposits produces an irregular surface, non-vertical walls, and better preservation of the original channel width (Harris, 1980). In cross section, primary sedimentary structures are evident, including scour-and-fill deposits, graded bedding, climbing ripples (ripple laminae), horizontal stratification, and cross-bedding (figure 11). The sandstone is composed of quartz grains and the conglomerates are principally composed of chert pebbles, but also contain fossil fragments. Sediment composition and transport direction suggest that clasts were eroded from the Sevier uplift to the west-southwest (Harris, 1980). These paleochannels were likely the last stage of fluvial deposition in Early Cretaceous time before the region was covered by predominantly marine shale deposited in the Late Cretaceous Mancos Sea. Based on published average long-term erosion rates (discussed previously, Nuccio and Condon, 1996; Nuccio and Roberts, 2003), the fluvial sediments at Site D (figure 1) have a maximum surface re-exposure age of 650,000 years, while older paleochannels at Site B (figure 1) have a maximum exhumation age of 1 million years (figure 4C).

Raised Curvilinear Features on Mars

Images from spacecraft orbiting Mars have revealed quasi-dendritic landforms (~200 km [120 mi] characteristic length), termed valley networks, which resemble terrestrial fluvial systems (for example, McCauley and others, 1972; Carr, 1996). However, liquid water is unstable under current atmospheric and temperature conditions on Mars. At most locations on Mars, year-round surface temperatures and pressures are below the triple point of water (273 K [32°F], 0.61 kilopascal [6.1 mbar]), so that liquid water will spontaneously boil and/or freeze (Haberle and others, 2001). The prevailing interpretation based on data collected from Mariner 9 (1971) and the Viking orbiters (1976–80) has been that most valley networks formed during an earlier warmer and wetter climate (for example, Mars Channel Working Group, 1983). High-resolution images (<100 m [330 ft] per pixel) from the Mars Orbiter Camera (MOC) aboard the Mars Global Surveyor (1997–2006), and the Thermal Emission Imaging System (THEMIS) aboard the Mars Odyssey (2002–present) show new details of the valley networks not recognized in the older, lower resolution data. For example, in northeast Arabia Terra (see figure 12 for locations of examples on Mars), the valley network does not have a well-defined termination or distal deposit in the Viking image (figure 13A). However, the MOC image shows that the valley floor extends beyond the area with well-defined walls as a low-relief plateau, an observation consistent with regional erosion of valley walls and preservation of the former valley floor as a local topographic high (figure 13B). The valley networks on Mars exhibit various states of preservation including partial or discontinuous exposure and inverted relief (Edgett and Williams, 2004; Williams and others, 2005). At multiple sites on Mars, similar ridge landforms are now recognized with some examples connected to traditional valley networks, while other examples are located in geologic settings not associated with valley networks, such as crater floors (Williams and Edgett, 2005). Burr and others (2006) advocated the nongenetic term "raised curvilinear features" (RCFs) for these bifurcating ridge landforms on Mars.

Individual RCFs extend in length from a few hundred meters to several tens of kilometers (~650 ft to 45 mi), have widths between 10 m and a few kilometers (~30 ft to 2.5 mi), and relief of as much as 50 m (170 ft) above the surrounding terrain (Burr and others, 2006). The Martian RCFs are interpreted to be the remnants of ancient fluvial channels now expressed in inverted relief based on their curvilinear and bifurcating appearance and their similarity to terrestrial fluvial landforms (Williams



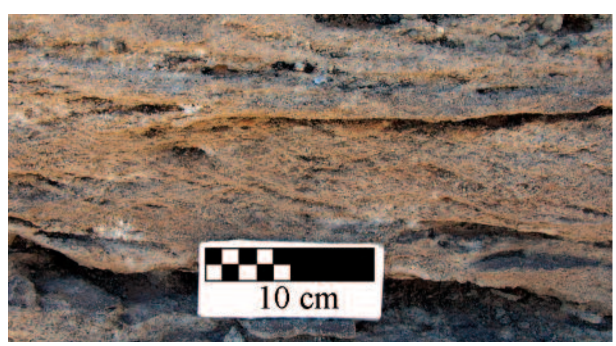


Figure 11. *Examples of stratification types exposed in vertical sections of paleochannel sediments at Site D. Top: sequence includes graded bedding exposures in trough cross-beds at base, horizontal stratification at mid-section, and channel-fill deposits at top. Bottom: climbing ripples exposed in point-bar deposit. Climbing ripples are well exposed in vertical section; however, ripple marks are rarely found on paleochannel surfaces. Scale bar in both images is 10 cm (3.9 in).*

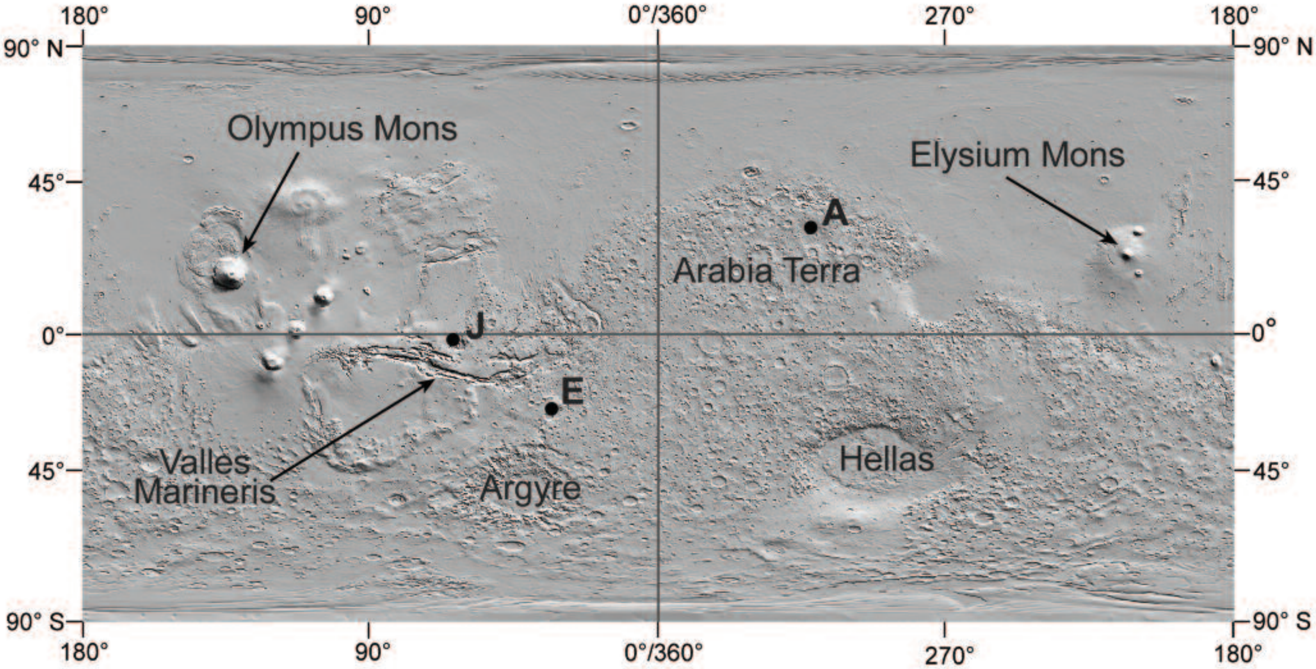


Figure 12. *Shaded-relief map of Mars with major surface features labeled. Lettered dots refer to site locations of Martian landforms described in paper: A = Arabia Terra, E = Eberswalde Crater, and J = Juventae Chasma. Illumination is from the north. Figure modified from shaded-relief map produced by MOLA Science Team (Neumann and others, 2001).*

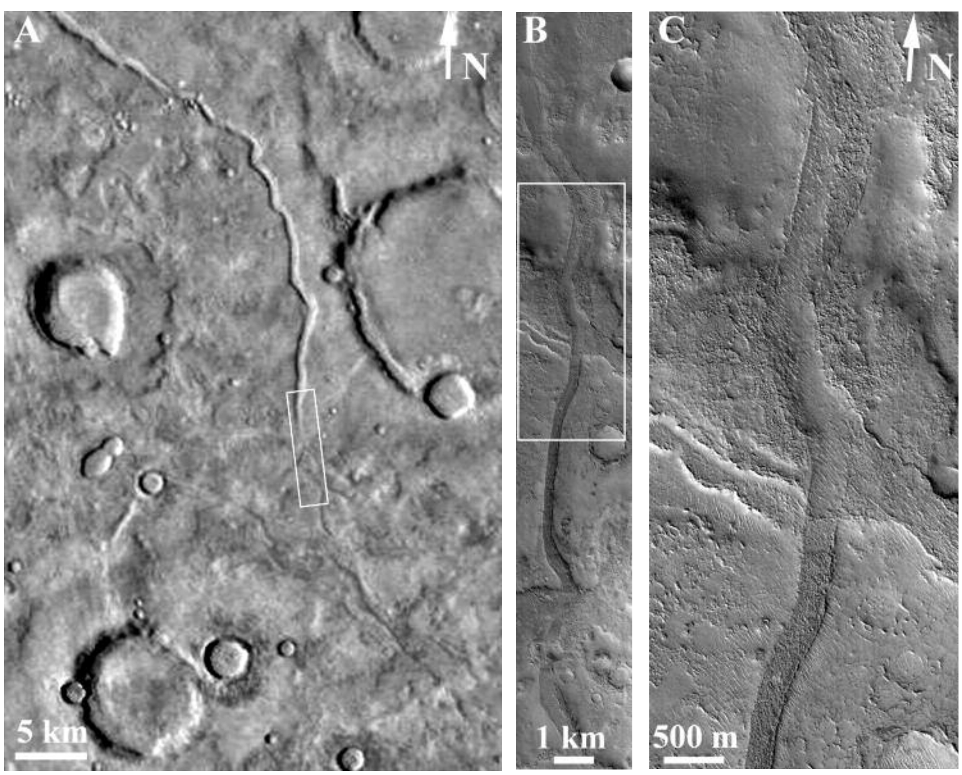


Figure 13. *(A) Viking image mosaic of unnamed valley network in Arabia Terra (33°N, 314°W; Site A in figure 12) that appears to disappear. White rectangle marks location of Mars Orbiter Camera (MOC) image displayed at right. Illumination is from left. (B) High-resolution image illustrates the transition in preservation of this landform at this location from a negative relief valley (top of image) to a positive relief, low-elevation plateau. This image is interpreted as a valley network that has sections preserved in inverted relief. White rectangle is location of enlarged image at right (C). Illumination is from lower left. MOC image ID R09-00568.*

and Edgett, 2005). [Alternative potential explanations for these landforms, for example eskers, still invoke surface overland flow of fluids (for example Burr and others, 2006, and references therein).] Altogether, the various network morphologies observed for RCFs on Mars document a range of paleofluvial environments attesting to a complex fluvial history on the planet; two examples are illustrated below.

A multi-lobe distributary fan complex, defined by cross-cutting ridges in the Eberswalde Crater (24.3° S, 33.5° W, figures 12 and 14), is interpreted to be a deltaic deposit preserved in inverted relief (Malin and Edgett, 2003; Moore and others, 2003). Sedimentary bedforms can be preserved in RCFs; this example illustrates migrating scroll bars within a meander loop. The presence of a cut-off meander attests to the persistent fluvial activity that occurred within this depositional system. Researchers, using numerical models of fan construction based on channel morphology, have advocated various estimates for the minimum formation time scale of the fan ranging from decades to over 100,000 years (Jerolmack and others, 2004; Bhattacharya and others, 2005).

Multiple examples of individual RCF network systems comparable in scale to terrestrial creeks formed by precipitation-fed surface runoff are concentrated on the plains around Valles Marineris (figures 12 and 15). Low-order tributaries are rarely seen in Martian fluvial landforms. However, these fine-scale branching networks of sinuous and meandering ridges are relatively high ordered for Martian drainage systems and have drainage densities ranging from 0.9 to 2.3 km^{-1} (1.5–3.7 mi^{-1}), values that are among the highest observed on Mars and comparable to terrestrial fluvial systems of the same scale (Williams and others, 2005). These RCFs are particularly noteworthy because they occur at different levels within the layered stratigraphy. In the past, these RCFs were buried. They were subsequently exhumed, presumably by eolian activity, to expose them at the surface. In figure 15B, a stratigraphically higher stratum has locally been preserved as remnant mesas and the crater in the upper center of the image that superposes the RCF. Rough order-of-magnitude discharges computed for these RCFs from the empirical Chezy-Manning equation and meander relations (approximately 10 to 20 cubic m per second [350–700 ft^3/s]) appear more consistent with bankfull peak discharge conditions than with persistent or continuous flow; these values are generally comparable to similarly sized fluvial networks on Earth (Williams and others, 2005).

In planetary science, the age of a terrain is determined by the number and size of impact craters observed (see Hartmann and Neukum, 2001, for a detailed discus-

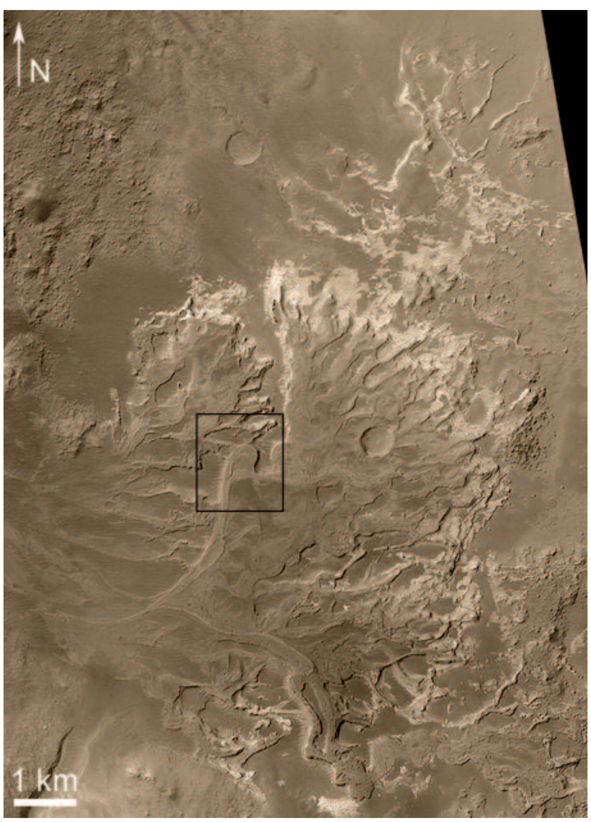


Figure 14. *Left: a false-color MOC image mosaic of portion of Eberswalde Crater (24.3°S, 33.5°W; Site E in figure 12). At this site, a multi-lobe distributary fan complex comprises cross-cutting ridges formed as a result of topographic inversion, likely due to wind erosion. Black rectangle is location of cut-out image enlarged at right. Right: the cutoff meander loop is direct evidence of persistent fluvial activity within the system. Individual scroll bars are preserved within the meander loop. Illumination is from the left. Image credit: NASA/JPL/Malin Space Science Systems.*

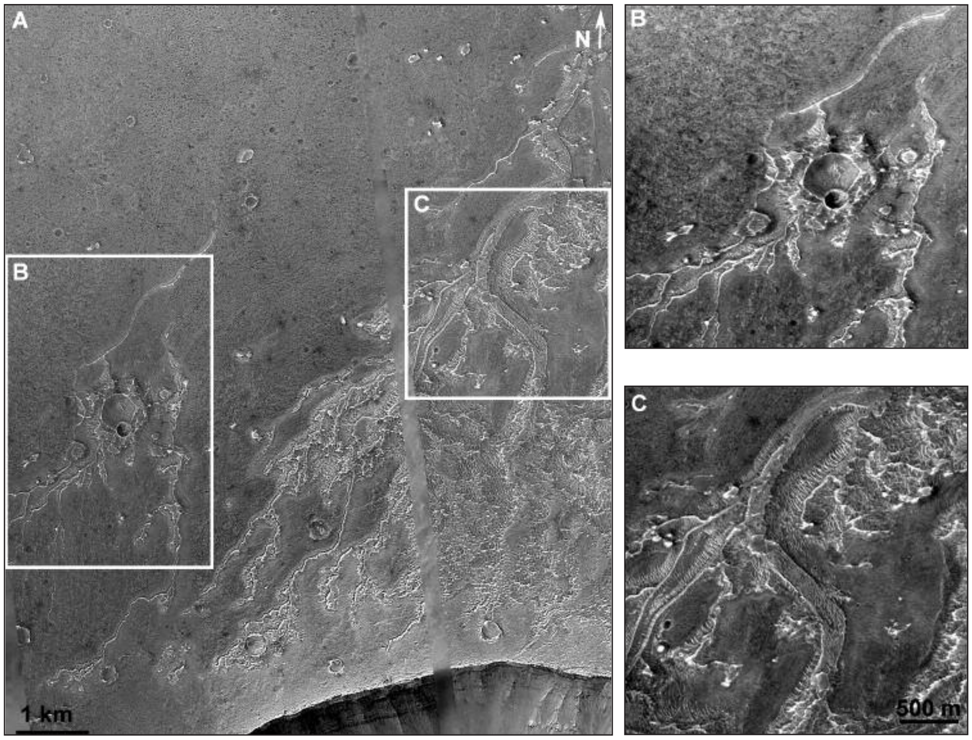


Figure 15. *(A) Examples of fine-scale sinuous inverted ridge networks located on plains above western rim of Juventae Chasma (4.5°S, 63.2°W; Site J in figure 11) in this MOC image mosaic. Relief at the distal margin of the fan complex is 100 to 200 m (330–650 ft) above the crater floor (Moore and others, 2003). (B) The ridge system at right has multiple, closely spaced low-order tributary segments, an attribute not commonly observed in Martian valley networks until the recognition of inverted channel systems in high-resolution orbital images. Illumination is from left. MOC image ID R09-02851. (C) A branching ridge network with a broadly sinuous trunk channel. Illumination is from left. MOC image ID R08-02192.*

sion of technique and issues with using crater-count chronologies). The time dependence of the crater size distribution is well known for the inner solar system (Neukum and others, 2001). Thus, the crater population of an area is used to assign an age within the three Martian epochs (intervals of several hundred million years to billions of years) defined by Tanaka (1986) based on stratigraphic mapping. The maximum formation age of an RCF can be determined by the youngest geologic unit intersected by the RCF. Raised curvilinear features have been observed on terrains that span the entire geologic history of Mars (Williams and others, 2005; Burr and others, 2006; Williams, 2007). Assuming this preliminary and rudimentary observation regarding formation age is valid (that the age of an extensive geologic unit can be applied to a small locality—the RCF—found within that geologic unit), then the RCFs record surface overland fluid flow that occurred periodically throughout Martian history. The stratigraphic context of valley networks and RCFs indicates that the fluvial processes that formed small-scale drainage systems on Mars were not confined to the earliest epoch, as has long been contended (for example, Mars Channel Working Group, 1983), but operated well past the earliest time of heavy impact cratering around 3.8 billion years ago. These valley systems observed today are the products of the combined forces of burial, erosion, and exhumation.

DISCUSSION

General Comparison

Raised curvilinear features on Mars are a key landform to understand the evolution and distribution through time of fluvial sedimentary processes on the planet. They are a physical record of the past climate and fluvial environments on Mars. In addition, RCFs are ideal sites for future Mars rover exploration as inverted paleochannels preserve sedimentary bedforms. The Martian RCFs are comparable in scale and network morphology to the inverted paleochannels in east-central Utah. These Utah sites afford the opportunity for ground truth and provide an Earth-based natural laboratory to collect data and assess models. Future investigation of these terrestrial analogs has application not just to understanding terrestrial landscape evolution, but also will help to constrain the formation history of similar landforms on Mars and will ultimately yield a more robust understanding of the history of water on the red planet.

The stages of formation of the inverted paleochannels in central Utah (figure 4) provide a conceptual framework for studying the Martian RCFs. Although many Martian RCFs exhibit evidence of past burial, it is unknown whether this is a key stage in the formation of these landforms. Conceivably, induration of the fluvial sediments and subsequent erosion are the minimum stages required to produce an inverted paleochannel. Questions remain regarding the minimum time scales of each phase in the formation of inverted paleochannels (figure 4) as well as the environmental conditions of the cementation history (near surface and/or diagenetic cements).

In contrast to the Utah inverted paleochannels, which were eroded by fluvial activity, eolian activity was likely the dominant erosive agent responsible for exhuming RCFs on Mars. Rates of eolian erosion vary greatly depending on many factors including wind velocity, sediment size, topography, and atmospheric density. For fine-grained, unconsolidated sediment, such as loess, vertical erosion rates due to wind on Earth can exceed the fluvial erosion rates estimated for the study region in Utah (for example, Basher and Painter, 1999). However, estimates of long-term erosion rates from surface observations by landers and rovers on Mars indicate minimal deflation (10^1 to 10^2 nm per thousand years [10^{-8}–10^{-7} ft/kyr]) for at least the past ~2 billion years, which is consistent with a dry and desiccating environment, and significantly higher rates (10^5 to 10^7 nm per thousand years [10^{-4}–10^{-2} ft/kyr]) during the first billion years of the planet's history based on crater degradation (Golombek and Bridges, 2000; Golombek and others, 2005). Recent simulations of Martian wind erosion based on general circulation models (GCMs) suggest that higher long-term eolian erosion rates (10^6 to 10^7 nm per thousand years [10^{-3}–10^{-2} ft/kyr]) are possible regionally in the past 1 billion years, rates that are consistent with removing several kilometers of easily eroded fine regolith within 100 million years (Armstrong and Leovy, 2005). The uncertainty in erosion rates, coupled with poorly constrained burial depths, make it difficult to estimate surface exposure ages for the Martian RCFs. Importantly, the inverted paleochannels in Utah are slowly eroding at present with the channel surfaces breaking down into blocks (figure 5) and undermining of softer underlying units leading to collapse of these ridges. Wind erosion (mechanical weathering) is less efficient at weathering indurated materials than fluvial erosion (chemical and mechanical weathering). Therefore, the environment on Mars may be more conducive to preserving these landforms for longer periods of time (millions if not billions of years) than on Earth.

Cementation of Paleochannels

The majority of Martian RCFs are likely the result of preservation of the fluvial channel floors via cementation. Examples of clast-armoring to preserve terrestrial exhumed paleochannels are poorly documented in the literature and this mechanism appears to be a complementary process to achieve induration of the fluvial sediments (for example, Maizels and McBean, 1990). In addition, coarse-grained deposits tend to occur in localized concentrations along a fluvial path (such as on the inside bends of meanders in point-bar deposits; for example, Ritter, 1986) and these sections would be preferentially protected from erosion. Thus, this mechanism alone would not explain the extensive branching networks (for example, figure 14) nor the degree of preservation (scroll bars, preservation of width along course, and so forth) observed in the Martian RCFs; however, both of these attributes are plausible outcomes from cementation. Lava infilling could explain some examples, but often RCFs are not associated with an obvious volcanic source and this mechanism would obscure sedimentary bedforms. Also, the generation of lava-capped channels requires a secondary process (volcanism), whereas cementation and armoring are by-products of the fluvial process that formed the channel. For these reasons, we infer that cementation is the dominant mechanism involved in indurating the RCFs.

The terrestrial analogs in central Utah illustrated in this paper are carbonate-cemented (calcite) paleochannels (Derr, 1974; Harris, 1980; Lorenz and others, 2006). [Localized quartz cement, both grain coating and pore filling, is reported by Lorenz and others, 2006.] The composition of the inferred cementing agent for Martian raised curvilinear features is unknown. Carbonate is a candidate cement that has been recognized in Martian meteorites (Bridges and others, 2001) and in low concentrations in Martian dust (Bandfield and others, 2003); however, carbonate-rich regions have not been detected yet (Bandfield, 2002; Bibring and others, 2006). Sulfate polyhydrates, another candidate cement, have been identified in spectral data (Bibring and others, 2005, 2006) but are not associated with Martian RCFs in the data acquired to date. Element and mineral analysis by surface landers indicates the presence of several other potential cements including sulfates (jarosite, gypsum, epsomite), iron oxides (hematite), silica, clay (nontronite), and halides (for example, Landis and others, 2004; Glotch and others, 2006). Certain depositional environments can yield a range of chemical cements suggesting that the formation history and relative timing will be similar even though the chemical composition may vary. For example, evaporation of water can produce sulfates or carbonates, among other outcomes, depending on initial water composition.

Despite the potential differences in cement type between Earth and Mars, study of terrestrial analogs is extremely valuable and our best avenue to constrain the conditions and time scales involved in landform genesis. The sequence of events and formation rates involved in the generation of these landforms will be grossly similar for paleochannels regardless of the composition of the cementing agent.

SUMMARY

- A range of fluvial environments preserved as inverted paleochannels in east-central Utah affords a unique opportunity to study the diversity of inverted paleochannels present in a small geographic region.
- The environmental conditions that generate inverted paleochannels are ideal for preserving fluvial sediments and internal sedimentary structures in three dimensions.
- The morphology of terrestrial inverted paleochannels is similar to comparably sized RCFs on Mars, suggesting a similar formation history.
- Inversion of relief is a common process of landscape evolution that results in the preservation of paleochannels as topographic ridges on both Earth and Mars.
- Although there are likely variations in the formation history between the terrestrial inverted paleochannels and Martian RCFs, including differences in cement composition and erosional agent, further study of these landforms on Earth will help elucidate the magnitude and relative timing of fluvial activity on Mars.

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